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Liquefaction at Moss Landing during the 1989 Loma Prieta earthquake

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ABSTRACT: The October 17, 1989 Loma Prieta earthquake caused extensive liquefaction in the coastal area of Moss Landing, California. The Moss Landing Marine Laboratory (MLML) was damaged beyond repair by liquefaction of the natural subsurface soils and lateral spreading and differential settlement of the site. In contrast, permanent ground displacements at the site of the new Monterey Bay Aquarium Research Institute (MBARI) technology building and pier were small and these facilities were undamaged. This paper describes some of the liquefaction effects in the Moss Landing area including the liquefaction failure of the MLML and the absence of liquefaction damage at the MBARI facilities.

1 INTRODUCTION

The October 17, 1989 Loma Prieta earthquake caused extensive liquefaction and ground failure throughout the San Francisco Bay and Monterey Bay regions of California. Liquefaction generally occurred in areas that had been previously identified as having a high liquefaction potential and which had liquefied during the Great 1906 San Francisco earthquake (Youd and Hoose, 1978; Seed and others, 1990).

Liquefaction was widespread in the coastal area of Moss Landing located about 25 kms south of the epicenter as shown in Figure 1. Liquefaction was particularly severe on the Moss Landing spit, a 150- to 300-meter-wide shoreline peninsula deposited by beach sedimentation and by the Salinas river. Water and sewer services on the spit could not be fully restored for a period of over 3 months, thus severely affecting operation of several commercial fisheries, the Monterey Bay Aquarium Research Institute (MBARI) facilities, and the Moss Landing Harbor.

The Moss Landing Marine Laboratory (MLML) was damaged beyond repair by liquefaction of the natural subsurface soils. Even though the building was practically torn apart at the foundation the structure did not collapse and no casualties or severe injuries occurred among the approximately 50 people occupying the facility at the time. North of the MLML there was evidence of liquefaction, settlement and lateral spreading along the entire length of the spit. However, damage from liquefaction to other buildings was not as severe as to the MLML. At the site of the new MBARI technology building and pier, permanent lateral ground displacements were small and these facilities were essentially undamaged.

The purpose of this paper is to describe some of the observed liquefaction effects in the Moss Landing area including the liquefaction failure at the site of the MLML and the absence of damage at the MBARI facilities.

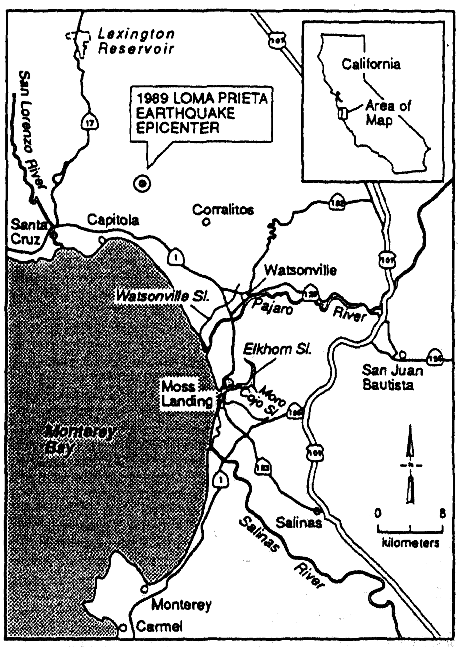

Figure 1. Map of Monterey Bay region.

2 SETTING

Moss Landing is located on the eastern shoreline of Monterey Bay approximately midway between Santa Cruz and Monterey, about 12 kms southwest of Watsonville (Fig. 1). Prior to the 1906 San Francisco earthquake the Salinas River flowed into Monterey bay through the Moss Landing Harbor to an outlet about 2.5 kms north of Moss Landing. As shown in Figure 2 the harbor now occupies part of the old river channel.

The area is underlain by a sequence of Holocene deposits consisting of relatively thick sands offshore and estuarine and fluvial deposits onshore up to about 55 ms deep. The Moss Landing spit is underlain by littoral soils deposited in a shoreline environment within the zone of tidal fluctuation. The soils are predominantly sands with interbedded silts and clays. They are underlain by Pleistocene and Miocene deposits to a depth of about 2.1 kms at which oil exploration logs indicate Mesozoic granite bedrock is encountered.

3 EARTHQUAKE GROUND MOTIONS

No ground motion recording instruments were operating near Moss Landing at the time of the 1989 Loma Prieta earthquake. However, several instruments from the California Strong Motion Instrumentation Program (CSMIP) recorded the earthquake motions in the region.

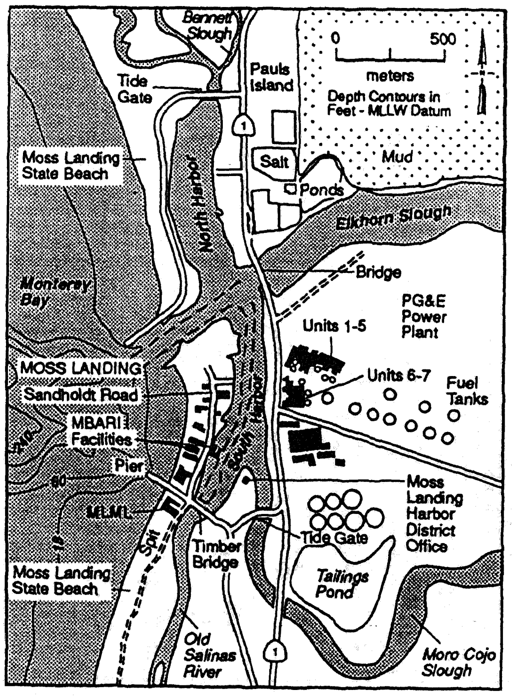

Figure 2. Map of Moss Landing area.

Table 1. Recorded peak horizontal accelerations in region near Moss Landing.

Recording Station	Epicentral Distance (kms)	Distance to Source (kms)	Site Conditions	Peak Horizontal Acceleration (g)
Watsonville	18	8	Alluvium	0.39
San Juan Bautista	33	20	Stiff Alluvium	0.15
Salinas	46	36	Alluvium	0.12
Monterey	49	47	Rock	0.07

The peak horizontal accelerations recorded at the strong motion stations closest to Moss Landing are presented in Table 1.

Based on the ground motions recorded in the region, the results of numerical simulations, the level of shaking intensity reported by occupants of the MLML, and the level of shaking inferred from damage to structures and their contents not affected by liquefaction, it is estimated that the peak horizontal acceleration at Moss Landing was about 0.25 g (Mejia, 1992).

4 OVERVIEW OF LIQUEFACTION EFFECTS IN MOSS LANDING AREA

Liquefaction resulted in extensive lateral spreading and settlement of the access road to the Moss Landing State Beach west of the Moss Landing North Harbor (Fig. 2) leaving numerous motorists stranded. The road embankment at the tide gate across Bennett Slough slumped about 1.5 ms as a result of liquefaction and lateral spreading of the foundation soils. The Highway 1 bridge across Elkhorn Slough was intermittently closed for repairs for a few days after the earthquake. Liquefaction of the subsurface natural soils resulted in settlements and lateral deformations of the approach fills of about 15 cms.

The 2,000-mW Pacific Gas and Electric Power Plant at Moss Landing suffered relatively minor damage during the earthquake except at the 500-kV switchyard where many pieces of electrical equipment including several transformers were damaged. In contrast, there was considerable liquefaction damage in the area of the parking lot of the Moss Landing Harbor District offices. This is an area of filled ground and liquefaction appears to have occurred predominantly in the fill. Liquefaction damage along the spit was severe and extended to the northern end of the spit and offshore (Greene and others, 1991).

Evidence of lateral spreading and liquefaction in the form of sinuous cracking and occasional graben-like features could be followed for several hundred feet along Moss Landing State Beach south of the MLML.

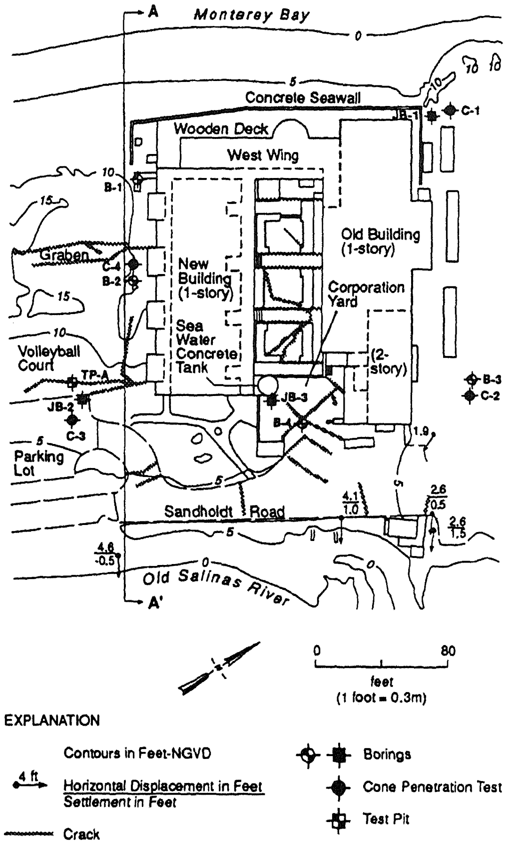

Figure 3. Site plan of Moss Landing Marine Laboratory.

The south access road to the spit, beginning at the south tide gate on the Old Salinas river and joining Sandholdt Road at the single-lane timber bridge across the river, was damaged as a result of settlement and lateral deformations associated with liquefaction. However, for a few weeks this road was the only land access to the spit since the timber bridge across the river was heavily damaged during the earthquake. Liquefaction resulted in over 1.2 ms of settlement of the approach fill and about 30 cms of lateral deformation towards the river. The bridge piles near the approach were shifted laterally at the mudline by about 15 cms rendering the bridge impassable except by light emergency vehicles.

5 MOSS LANDING MARINE LABORATORY

As shown in Figure 3, the MLML consisted of two main buildings and a west wing surrounding a courtyard. The northern building was a one- and two-story wood-frame structure with a raised wood floor, founded on shallow footings. The southern building and the west wing were one-story wood-frame-and-shear-

Figure 4. Racking of director's office at south west corner of MLML.

wall structures with slab-on-grade floors. The eastern half of the southern building was founded on cast-in-place concrete piers 40 cms in diameter and up to 5.5 ms deep. The western half and the west wing were founded on shallow strip footings.

The facility was destroyed by the earthquake and the buildings have since been demolished. The general pattern of damage to the facility indicated lateral spreading of the entire site from soil liquefaction. The buildings spread 0.7 to 1.2 ms at the ground surface in the east-west direction. Displacements in the north-south direction were relatively small. Figure 4 shows racking of the director's office at the southwest corner of the facility. Measured lateral and vertical displacements are shown in figures 3 and 5. The total extension of the spit from lateral spreading at the site appears to have ranged from about 1.3 ms on the north side of the laboratory to 2.1 ms on the south side. This difference in displacements appears to be related mainly to slight differences in topography between the north and south sides of the site and slight differences in soil conditions.

As shown in Figure 3, lateral spreading resulted in extensive cracking throughout the site. The southern building suffered severe cracking in the foundation and slab floor. Cracks up to 15 cms wide developed in the slab and separations of up to 25 cms occurred between building floors and walls. The northern building also suffered severe cracking at the roof and foundation levels with separations in excess of 45 cms at some locations.

Soil boils, which geysered up to 1 meter, flowed for 30 to 45 minutes after the earthquake at the volleyball court south of the laboratory (Greene and others, 1991). The soil boil ejecta consisted of predominantly fine grained clayey silt although medium-grained sand also flowed to the surface at this location. Soil boils of medium-grained sand erupted at the southeast corner of the southern building and on the north side of the laboratory. In addition, there was considerable

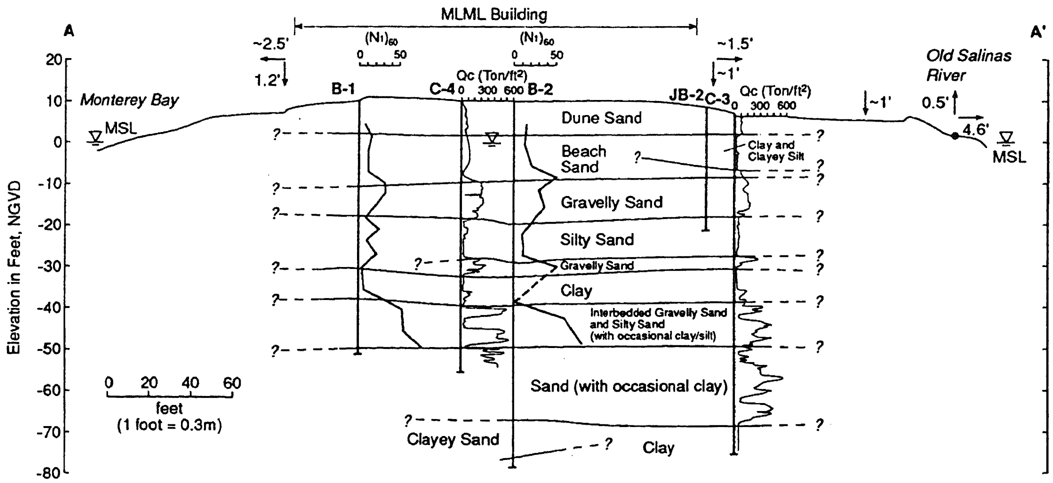

Figure 5. Subsurface conditions at Moss Landing Marine Laboratory.

upwelling of muddy water through cracks in the corporation yard pavement shown in Figure 3.

As shown in Figure 5, the MLML site is underlain by dune, beach, marshland, and alluvial deposits. Ground failure at the site was the result of liquefaction of the loose to medium dense beach sand below the water table including the beach sand below the clayey silt underlying the east side of the site. The soil boil ejecta at the volleyball court indicate that the clayey silt underlying the dune sand in this area also appears to have liquefied (Mejia, 1992).

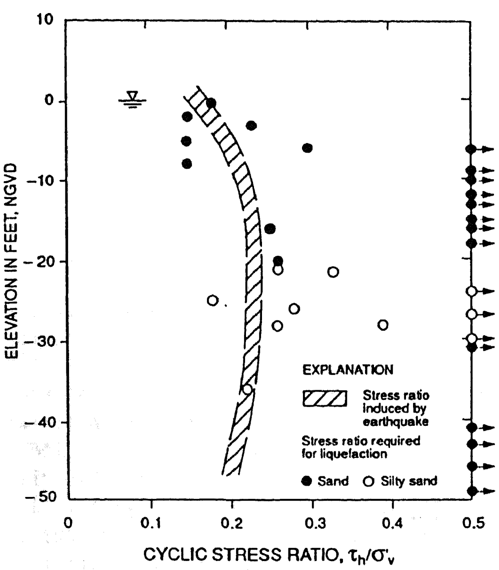

Figure 6. Comparison between cyclic stress ratio induced by earthquake and stress ratio required for liquefaction based on SPT data at MLML.

Liquefaction of the beach sand would be anticipated based on the SPT blow count data from borings at the site and currently available empirical correlations between normalized blow count $(N_1)_{60}$ and liquefaction resistance. Figure 6 shows a comparison between the cyclic stress ratio induced by the earthquake and the stress ratio required for liquefaction calculated using the procedures outlined by Seed and others (1985). The figure shows that liquefaction would be expected in the beach sands. The figure also indicates that the dense gravelly sands probably did not liquefy and that limited liquefaction may have occurred in the silty sand below.

6 MONTEREY BAY AQUARIUM RESEARCH INSTITUTE FACILITIES

The MBARI facilities are located about 240 ms north of the MLML on the Moss Landing spit. A site plan of the facilities is shown in Figure 7. They consist of a

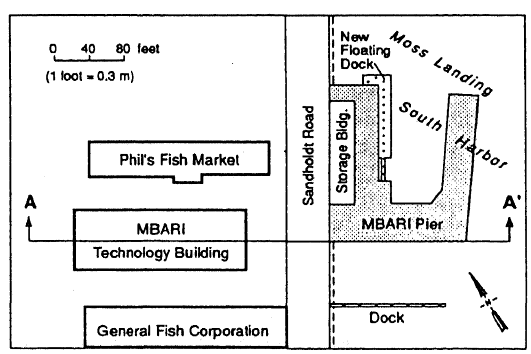

Figure 7. Site plan of Monterey Bay Aquarium Research Institute facilities.

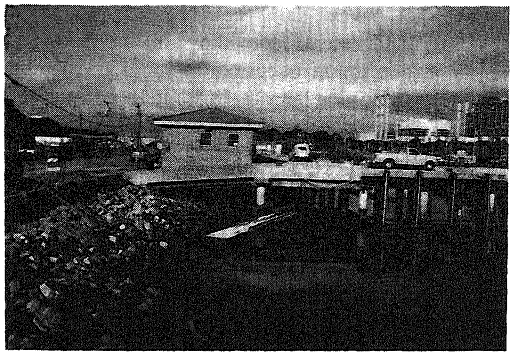

Figure 8. Appearance of MBARI pier three days after the earthquake.

reinforced concrete pier founded on 45-cm-diameter prestressed concrete piles and a high one-story building founded on spread footings known as the technology building. A one-story masonry storage building is built on the pier. The facilities were built in 1988 and 1989 and were being completed at the time of the earthquake.

In contrast to the MLML, the MBARI facilities performed very well during the earthquake. The technology building was undamaged by the shaking and there was no evidence of damage to the foundation or concrete floor. Permanent ground deformations at the site were small and the building appears to have settled uniformly. There was no evidence of sand boils in the immediate area surrounding the building. Sand boils erupted on Sandholdt Road in front, and north and south of the pier.

The MBARI pier was essentially undamaged by the earthquake. Figure 8 shows a view of the south side of the pier. Evidence of small movements in the form of minor concrete spalling could be observed at the joints between some of the piles and the deck. Lateral displacements of the edge of the road towards the harbor were about 25 cms and 8 cms just north and south of the pier, respectively. However, the pier appears to have displaced laterally less than about 3 cms towards the harbor.

The soil conditions in the area are shown in Figure 9. Based on the observed lack of damage, it is clear that widespread liquefaction, such as that observed at the MLML site, did not occur at the site of the technology building. The small deformations observed around the building suggest that localized liquefaction may have occurred in the medium dense to dense sand underlying the site. The marked difference in observed performance between the MLML and the MBARI technology building sites appears to be due to the apparently higher density of the near surface sands at the MBARI site.

The sand boils and deformations observed along Sandholdt Road indicate that liquefaction occurred in the near-surface loose to medium dense sands underlying the road. Based on the observed difference in lateral displacements of the pier and the waterfront slopes to the north and south, it appears that the pier buttressed the liquefied soils and prevented larger lateral deformations from developing on Sandholdt Road in front of the pier and possibly on the building sites across the road.

The apparent distribution of liquefaction at the site of the MBARI facilities is consistent with SPT blow count data at the site and the empirical correlations between $(N_1)_{60}$ blow count and liquefaction resistance proposed by Seed and others (1985). Figure 10 shows a comparison between the cyclic stress ratio induced by the earthquake and the stress ratio required for liquefaction calculated from the $(N_1)_{60}$ blow counts at the site. Based on the SPT data, limited liquefaction would be expected in the sands underlying the technology building. More widespread liquefaction would be expected in the sands in the pier area in good agreement with the observed surface evidence.

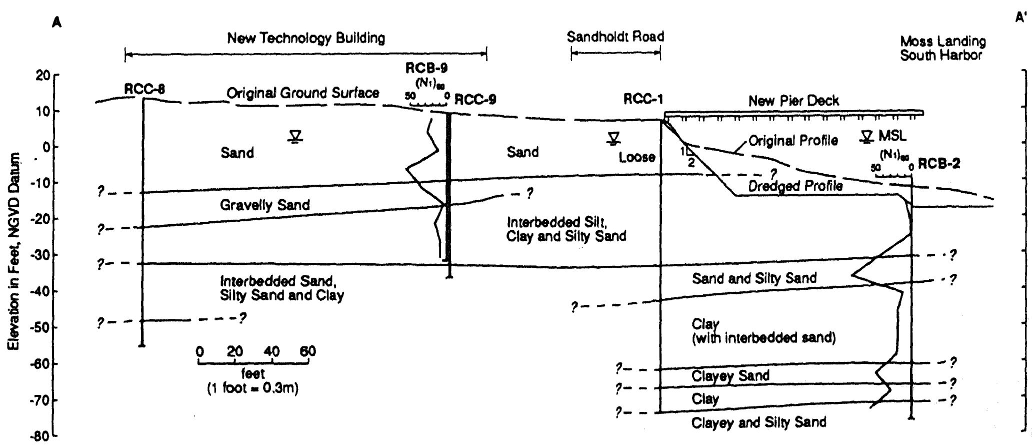

Figure 9. Subsurface conditions at Monterey Bay Aquarium Research Institute facilities.

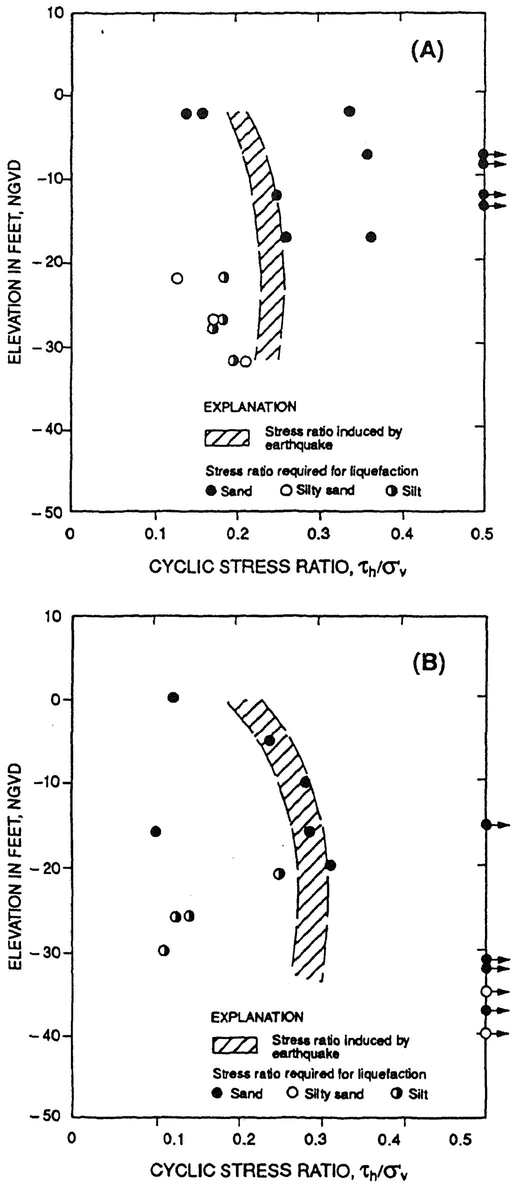

Figure 10. Comparison between cyclic stress ratio induced by earthquake and stress ratio required for liquefaction based on SPT data. A. MBARI technology building. B. MBARI pier.

7 SUMMARY AND CONCLUSIONS

The October 17, 1989 Loma Prieta earthquake caused extensive liquefaction and ground failure in the coastal area of Moss Landing. The ground motions in the area although strong were not particularly severe. It is estimated that the peak horizontal ground surface acceleration at Moss Landing was about 0.25 g.

The MLML was damaged beyond repair by liquefaction and lateral spreading in the east-west direction. Liquefaction occurred in loose to medium dense sands underlying the site. In addition, liquefaction appears to have occurred in a marshland deposit of clayey silt underlying the eastern side of the site.

In contrast to the MLML, the MBARI facilities performed very well during the earthquake. The main reasons for the marked difference in performance between the MBARI facilities and the MLML appear to have included the more favorable soil conditions at the site of the technology building which did not liquefy extensively, the type of construction used for the building which was not susceptible to damage from small ground deformations, and the buttressing action of the pier on the liquefied soils along Sandholdt Road which prevented larger deformations from developing on the road in front of the pier.

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